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Abstract

INERTIAL FUSION ENERGY DEVELOPMENT APPROACHES FOR DIRECT AND INDIRECT-DRIVE

Consideration of different driver and target requirements for inertial fusion energy (IFE) power plants together with the potential energy gains of direct and indirect-drive targets leads to different optimal combinations of driver and target options for each type of target. In addition, different fusion chamber concepts are likely to be most compatible with these different driver and target combinations. For example, heavy-ion drivers appear to be well matched to indirect-drive targets with all-liquid-protected-wall chambers requiring two-sided illuminations, while diode-pumped, solid-state laser drivers are better matched to direct-drive targets with chambers using solid walls or flow-guiding structures to allow spherically-symmetric illuminations. R&D on the critical issues of drivers, targets and chambers for both direct and indirect-drive options should be pursued until the ultimate gain of either type of target for IFE is better understood.

1. INTRODUCTION

Initiation of the US National Ignition Facility (NIF) construction brings the possibility of achieving inertial fusion ignition and energy gain in the laboratory by about the year 2005. [**1**] The NIF will ultimately allow testing of both direct and indirect-drive targets, providing data needed to predict the requirements for each type of target to achieve the high gains necessary for inertial fusion energy (IFE). Beyond NIF, IFE will need a development facility (which will be referred to here as a Post-NIF Facility (PNF)) with an efficient driver capable of demonstrating high gain at high pulse rates. The feasibility of candidates for such a driver must also be demonstrated along with ignition and gain by 2005 to proceed with a PNF. The choice between direct and indirect-drive for a PNF must take into account the most appropriate driver for each type of target, and the projected lifetime of fusion chambers that are compatible with each target's illumination requirement. Figure 1 shows a conceptual

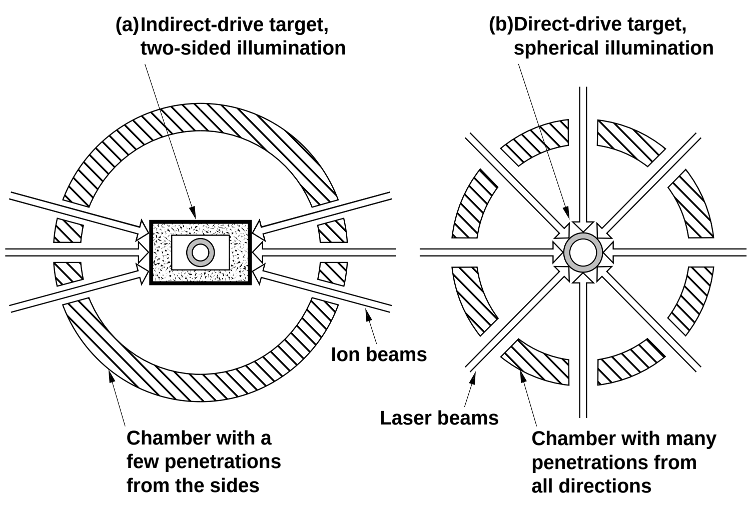

Fig. 1 Conceptual target designs for (a) indirect drive with ion beams and for (b) direct drive with laser beams, showing representative beam illumination geometry and penetrations through chamber walls in each case.

indirect-drive target driven by ion beams from two sides (Fig. 1a) and a conceptual direct drive target driven by lasers from all directions (Fig. 1b). For adequate symmetry, the ion indirect-drive case typically requires a minimum of 6 to 12 beams per side, while the laser driven direct-drive case typically requires of order 60 beams with spherically-distributed illuminations of the target. IFE power plant economics will depend strongly on both the driver energy requirement and cost (which depends on the driver efficiency and target gain), as well as on the reliability and lifetime of the fusion chamber with many penetrations for beam illuminations of the target.

2. DRIVER AND TARGET COMBINATIONS FOR IFE

There have been many design concepts of IFE power plants with different drivers [2], including studies for indirect drive based on heavy-ion accelerator (HIA) drivers [3] and on light-ion accelerator drivers [4], and for direct drive based on KrF gas laser drivers [5] and on diode-pumped solid-state laser (DPSSL) drivers [6]. All of these drivers could conceivably lead to an IFE driver. To contrast IFE development requirements for combinations of drivers, targets, and chambers based on direct and indirect-drive targets, this paper considers two cases: case 1- indirect-drive with HIA drivers and all-liquid-wall chambers (chambers such as described in [3]), and case 2- direct-drive with DPSSL drivers and dry-wall or guided-flow chambers (chambers such as described in [6]). In principle, both HIA and DPSSL drivers could be used for either direct or indirect drive. However, the choices of case 1 for indirect-drive IFE and case 2 for direct-drive IFE are based on several considerations to optimize each combination of driver and target:

(a) Product of projected driver efficiencies and target gains;
(b) Beam transport and chamber geometry for target illumination; and
(c) Shared technology development costs with other (non-IFE) applications.

2.1 Product of projected driver efficiencies and target gains

IFE power plant studies [2] find optimal designs require a minimum product of driver efficiency and gain ($\eta_d \cdot G$) > 7 to 10 to keep the recirculating power for the drivers to less than 35% to 25%, respectively, of the gross electric output of steam-turbine generators, where η_d is defined as the ratio of beam energy delivered to the target over the electrical energy input to the driver. With projected driver efficiencies of < 10% for DPSSL drivers and < 35% for HIA drivers, the above condition on ($\eta_d \cdot G$) leads to requirements for gains G greater than 70-100 for DPSSL drivers, and greater than 20 - 30 for HIA drivers. Given uncertainties in the ultimate target performance of mass-produced, injectable targets in a power plant environment, it is desirable to seek target designs capable of gains higher than what may ultimately be needed for each driver, e.g., G > 140 for DPSSL drivers, and G > 40 for HIA drivers would give a safety margin of ~two. Target designs for laser-driven indirect drive fall far short of this gain goal with a safety margin, but calculations by the University of Rochester Laboratory for Laser Energetics [7] suggest that such gains are energetically achievable for direct drive, if hydrodynamic and laser-plasma constraints are favorably resolved. For HIA drivers, ongoing work in 2-D indirect-drive target designs [8] suggests that gains over 40 should be achievable with two-sided illuminations.

2.2 Beam transport and chamber geometry for target illumination

A recent study of DPSSL drivers for indirect-drive [9] considered use of more than 340 laser beams, more than enough to meet direct drive symmetry requirements if applied to direct drive. The direct cost of all of the optics, including the laser optics, beam transport, and final optics, was estimated to be $116 M, less than 10% of the direct driver cost, so adapting this system to direct drive (work in progress) should not significantly change the driver cost. An all-liquid wall protection scheme such as the HYLIFE-II concept [3] is compatible with indirect drive with two-sided illumination as shown in Fig. 1a, but such a wall-protection scheme is incompatible with direct drive because it does not allow beam access from the top and bottom of the chamber. The large number of beam penetrations from all directions required for direct-drive may require a dry-wall chamber such as described in the SOMBRERO study [10], and which was incorporated in the DPSSL study [9]. Previous design studies for heavy-ion drivers [11, 12] have estimated a direct cost of beam transport (for beam bending and pulse drift-compression) plus final focusing of ~ $5M per beam. For HIA indirect-drive designs with 12 to 24 beams, these costs are less than 10 to 20% of the cost of the accelerator. However, for direct drive with more than 60 beams, heavy-ion beam transport costs would become much higher, especially if the beams had to be routed out of the ground plane of a single accelerator to provide spherically-distributed beam illuminations of the target with > 50 m beam ion bending radii.

2.3 Shared technology development costs with other applications

Minimizing development costs is also important in this era of tight research budgets. The DPSSL driver design in [9] incorporates many of the laser system features now being developed for the NIF, including a multi-pass amplifier architecture with large aperture Pockels cell optical switches, gas-cooling of the amplifier slabs (moderate cooling to reduce time between shots for the NIF) , high damage-fluence mirrors, spatial filters, and frequency-conversion crystals. HIA drivers using induction technology can utilize high-pulse rate solid state switching also being developed for application to advanced multi-pulse flash radiography machines [13]. Also, development of high-average power induction cores and pulsers, ion beam transport with gas neutralization, and many features of ion target physics are common to both light and heavy ion drivers, and these areas are being shared in a tri-lab cooperation between LLNL, LBNL and SNL [14].

3. CRITICAL DEVELOPMENT ISSUES FOR IFE

Figure 2 summarizes the top level development issues for IFE in the left column showing four development areas in target physics, driver technologies, target systems, and chamber technologies. Successful resolution of these individual issues over the next decade would allow the initiation of integrated systems development and testing in a Post-NIF Facility, followed by a Pilot Plant and finally a Demo, as shown in Fig. 2. The most important development need to qualify both the HIA and DPSSL driver options for a PNF is to test prototypes of each at the kJ beam energy level or higher, with beam quality sufficient for target interaction experiments. In the DPSSL case, it is important that the prototype tests be done at high pulse rates because of the influence of thermal gradients on wave-front distortions. Cost reduction R&D is important for the HIA components (cores, pulsers, quadrupole magnets and insulators), and for pump diode arrays for the DPSSL, to reduce the cost of these prototypes as well as to reduce the projected IFE driver costs.

Eventual 3-D target designs are needed to refine the driver requirements for both direct and indirect-drive approaches. Qualified high gain target designs, together with the development of adequately smooth DT cryolayers are also needed to guide later R&D on methods to mass manufacture such targets at low cost, with adequate precision, and with sufficient robustness to survive acceleration and injection into hot fusion chambers. More work is also needed on beam transport to targets in the chamber, particularly, on final focusing with partial beam neutralization in the case of heavy-ions, and on beam transport through gas-filled chambers and beam tubes for mitigation of damage to the final optics from soft x-rays and target debris in the case of lasers. Selection of chamber concepts for direct and indirect-drive cases will depend critically on evaluation of wall-protection schemes that are compatible with the beam-illumination geometry required for each type of target. More international cooperation in all of these critical developments would be important for IFE success.

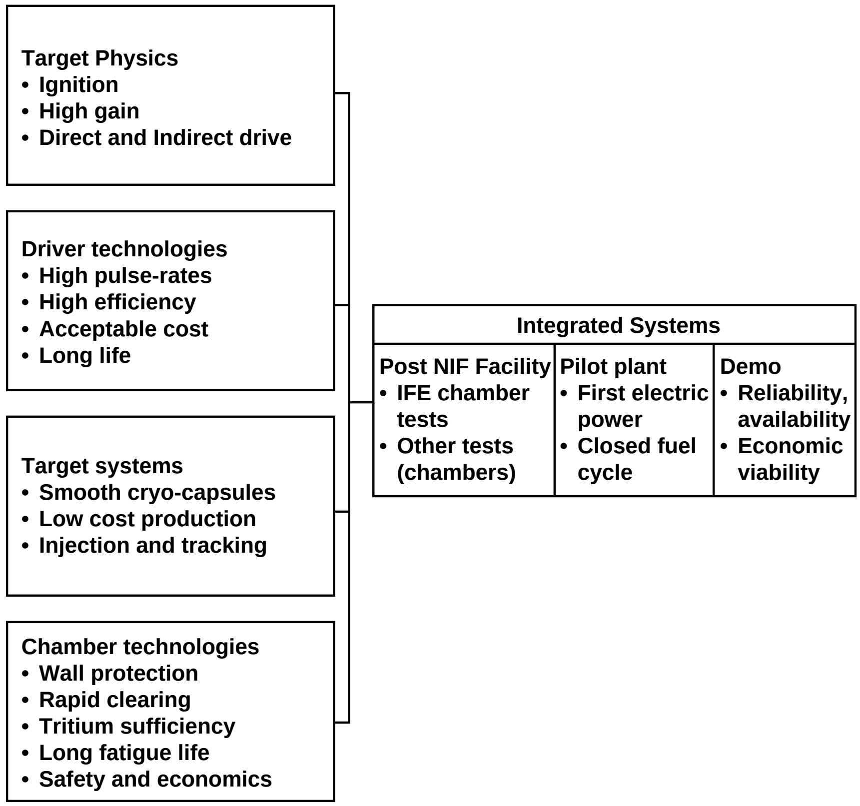

Fig. 2 Research and development to resolve critical development issues preceed integrated systems tests for IFE development.

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